

# THE GROUND SCALAR NONET AND D DECAYS

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## Abstract

A short review on light scalar mesons is performed both in experiment and theory. A naive model, constrained by D branching ratios, is derived in order to make predictions on the wave functions of the  $f_0(600)$  and  $a_0(980)$  mesons. This leads us to compute transition form factors between the pseudoscalar  $B$  and scalar mesons.

## 1 What is a light scalar meson?

Up to now, there is no global agreement on the interpretation of light mesons with vacuum quantum numbers: the scalar mesons[1]. At least, one can list two isovectors  $a_0(980)$  and  $a_0(1450)$ , five isoscalars  $f_0(600)/\sigma$ ,  $f_0(980)$ ,  $f_0(1370)$ ,  $f_0(1500)$  and  $f_0(1710)$ , and finally three isodoublets  $K_0^*(800)/\kappa$ ,  $K_0^*(1430)$  and  $K^*(1950)$ . One possible way to understand the light scalar spectrum may be to classify scalars according to their masses, i.e. below and beyond one GeV. Following this proposal, a first group with masses below one GeV (first nonet) contains  $f_0(600)$ ,  $K_0^*(800)$ ,  $f_0(980)$  and  $a_0(980)$ . A second group with a mass beyond one GeV (second nonet) includes  $f_0(1370)$ ,  $K_0^*(1430)$ ,  $a_0(1450)$ ,  $f_0(1500)$ ,  $f_0(1710)$

and  $K^*(1950)$ . Moreover, scalar mesons within their own group are built up according to the hypercharge,  $Y$ , and the isospin projection along the z-axis,  $I_z$ . The latter group being beyond the scope of this note, let us focus on the former group of light scalars so-called the first  $SU(3)$  nonet.

## 1.1 The first $SU(3)$ nonet

Following the spirit of the quark model, the  $f_0(600)$  meson with quantum numbers  $I^G(J^{PC}) = 0^+(0^{++})$ , the  $K_0^*(800)$  meson with quantum numbers  $I^G(J^P) = \frac{1}{2}^+(0^+)$ , the  $f_0(980)$  meson with quantum numbers  $I^G(J^{PC}) = 0^+(0^{++})$  and the  $a_0(980)$  meson with quantum numbers  $I^G(J^{PC}) = 1^-(0^{++})$  constitute altogether the first scalar meson nonet given in fig.1. Regarding masses and widths, from the PDG[2], one has  $M_{f_0(600)} = 400 - 1200 \text{ MeV}$ ,  $\Gamma_{f_0(600)} = 600 - 1000 \text{ MeV}$ ,  $M_{K_0^*(800)} = 672 \pm 40 \text{ MeV}$ ,  $\Gamma_{K_0^*(800)} = 550 \pm 34 \text{ MeV}$ ,  $M_{f_0(980)} = 980 \pm 10 \text{ MeV}$ ,  $\Gamma_{f_0(980)} = 70 \pm 30 \text{ MeV}$ , and  $M_{a_0(980)} = 985.1 \pm 2.7 \text{ MeV}$ ,  $\Gamma_{a_0(980)} = 75 \pm 25 \text{ MeV}$ , respectively. Various theoretical approaches in the study of different processes yield the following values for the pole of the  $f_0(600)$ [3]:

$$\begin{aligned} (489 \pm 26) - i(173 \pm 26) , \quad D^+ \rightarrow (\pi^+ \pi^-) \pi^+ , \\ (541 \pm 39) - i(252 \pm 42) , \quad J/\Psi \rightarrow \omega(\pi^+ \pi^-) , \\ (470 \pm 30) - i(295 \pm 20) , \quad \pi\pi \rightarrow \pi\pi , \end{aligned}$$

for the pole of the  $K_0^*(800)$ [3]:

$$\begin{aligned} (721 \pm 61) - i(292 \pm 131) , \quad D^+ \rightarrow (K^- \pi^+) \pi^+ , \\ (841 \pm 82) - i(309 \pm 87) , \quad J/\Psi \rightarrow K^+ \pi^- K^- \pi^+ , \\ (722 \pm 60) - i(386 \pm 50) , \quad K\pi \rightarrow K\pi , \end{aligned}$$

for the pole of the  $f_0(980)$ [3]:

$$\begin{aligned} (998 \pm 4) - i(17 \pm 4) , \quad J/\Psi \rightarrow \phi \pi^+ \pi^- , \\ 994 - i14 , \quad \pi\pi \rightarrow \pi\pi \text{ and } KK , \end{aligned}$$

and for the pole of the  $a_0(980)$ [3]:

$$(1036 \pm 5) - i(84 \pm 9) , \quad \bar{p}p \rightarrow \eta\pi\pi \text{ and } \omega\eta\pi^0 .$$

This non-exhaustive list of experimental and theoretical values underlines very well the difficulties we have in understanding the structure and properties of the scalar mesons.

## 1.2 Experimental evidences of scalar mesons

Unlike the difficulties to describe scalar mesons within a consistent theoretical framework, there are clear and unambiguous experimental evidences[4] of light scalar mesons. Some of these indications also give crucial informations on their internal quark structure.

### 1.2.1 Observations

Let us start with a few experimental signals provided by several collaborations. Regarding the  $f_0(600)$  meson[5], which mainly decays into  $\pi\pi$ , it has been observed in various processes. The phase shift of elastic  $\pi\pi$  scattering, when applying the Watson theorem and Roy equations, indicates the existence of  $f_0(600)$ . The E791 and FOCUS collaborations using isobar model (sum of Breit Wigner resonances) have also reported the  $f_0(600)$  meson in  $D^+ \rightarrow \pi^+\pi^-\pi^+$  decay. Another way of observing  $f_0(600)$  is related to the  $pp \rightarrow p(\pi\pi)p$  central production (GAMS collaboration) where a double pomeron ( $\rightarrow \pi\pi$ ) governs the process at small momentum transfers between the protons. The BES and DM2 experiments have also noticed the  $f_0(600)$  meson when the  $\pi\pi$  angular distribution in  $J/\psi \rightarrow f_0(600)\omega \rightarrow \pi\pi\omega$  was analyzed. For the  $K_0^*(800)$  meson[6], which mainly decays into  $K\pi$ , two different analysis have drawn positive conclusions on its existence: firstly, the phase shift of elastic  $K\pi$  scattering which was obtained from pion production by the LASS collaboration or from  $D^+ \rightarrow K^-\pi^+\pi^+$  by the FOCUS collaboration. Secondly, the E791 collaboration has also used an isobar model applied to  $D^+ \rightarrow K^-\pi^+\pi^+$  decay requires the  $K_0^*(800)$  for having a good fit of angular distributions. As regards the  $f_0(980)$  meson[7], which mainly decays into  $\pi\pi$  and  $KK$ , two major observations have been made. The BES II collaboration in  $J/\Psi \rightarrow \phi\pi^+\pi^-$  and  $J/\Psi \rightarrow \phi K^+K^-$  decays has found prominent signals when data were fitted with a Flatté formula. Another signal has also been observed in  $D_s^+ \rightarrow \pi^-\pi^+\pi^-$  decay by the E791 collaboration. The Dalitz plot analysis leads to suggest that a significant contribution is assumed to come from the  $f_0(980)\pi^+$  channel and hence gives an experimental evidence of the scalar  $f_0(980)$ . Concerning the  $a_0(980)$  meson[8], which mainly decays into  $\eta\pi$ , one of the first signal was provided by the E852 collaboration using the  $\pi^-p \rightarrow \eta\pi^+\pi^-n$  reaction at  $18.3\text{GeV}/c^2$ . The mass and width of the  $a_0(980)$  meson were independently determined so that it gave a first clear signal of this scalar state.

### 1.2.2 Quark structure

The internal quark structure of light scalar is still controversial and only experimental observations can be used to test theoretical hypothesis[4]. For example, let us consider here the case of  $f_0(980)$  where several collaborations have confirmed the  $s\bar{s}$  component of  $f_0(980)$ : the branching ratios (provided by the collaboration DM2 as well as by the PDG) of  $\mathcal{B}r(J/\psi \rightarrow f_0(980)\phi) = (3.2 \pm 0.9) \times 10^{-4}$  and of  $\mathcal{B}r(J/\psi \rightarrow f_0(980)\omega) = (1.4 \pm 0.5) \times 10^{-4}$  being different leads to a quark mixing in terms of  $u\bar{u}$  and  $s\bar{s}$  in  $f_0(980)$ . Finally, let us have a look at the  $a_0(980)$  scalar for which the collaboration KLOE[9] has given the branching ratios for radiative  $\phi$  decays:  $\mathcal{B}r(\phi \rightarrow \gamma f_0(980)) = (2.4 \pm 0.1) \times 10^{-4}$  and  $\mathcal{B}r(\phi \rightarrow \gamma a_0(980)) = (0.60 \pm 0.05) \times 10^{-4}$ . The radiative decay  $\phi \rightarrow \gamma a_0(980)$  which cannot proceed if  $a_0(980)$  is a  $\bar{q}q$  state can be however nicely described in the kaon loop mechanism. This suggests a admixture of the  $K\bar{K}$  component (4-quark state) which is in contradiction with assuming  $a_0(980)$  as a 2-quark state. Altogether, observing that  $a_0(980)$  and  $f_0(980)$  are almost degenerate, one should have a  $s\bar{s}$  component in  $a_0(980)$  that cannot be since it is an  $I = 1$  state.

### 1.3 Various theoretical models

The fundamental structure of scalar mesons remaining unclear, together with the difficulties related to experimental observation of the effects of light scalars in different processes, have generated a large variety of theoretical models on the market, each of them claiming to explain the structure of light scalars below and beyond one GeV. At least, five open-roads can be followed: the simplest one is the well-known  $q\bar{q}$  state for describing light scalars, then the  $q\bar{q}$  state plus glueball, then the four quark states  $(qq)(\bar{q}\bar{q})$ , and finally the mesonic molecules. Let us give a brief overview of their main characteristics[10]. a) The  $q\bar{q}$  state model where the  $q\bar{q}$  L=0 nonet ( $f_0(600)$ ,  $K_0^*(800)$ ,  $a_0(980)$  and  $f_0(980)$ ) is basically built up similarly to the  $q\bar{q}$  L=1 nonet ( $\pi, \rho...$ ). This model however cannot explain why  $a_0(980)$  and  $f_0(980)$  are not degenerate, why the  $a_0(980)$  and  $f_0(600)$  have the same number of non strange quarks but are not degenerate, etc... b) The  $q\bar{q}$  state plus glueball model where, according QCD expectations, the lightest glueball should be a scalar particle with quantum numbers  $(J^{PC}) = (0^{++})$ . In such scenario, the glueball is considered as a very broad object with a width of the order of its mass. It works rather well for scalar particles with masses beyond one GeV. c) The four quark states  $(qq)(\bar{q}\bar{q})$  model which allows one to have two configurations in color space:  $\bar{3}3$  and  $6\bar{6}$ . They can therefore rearrange to form a  $(q\bar{q})(q\bar{q})$  scalar state. d) Finally, the mesonic molecule model which is similar to the  $(qq)(\bar{q}\bar{q})$  case but considering only mesonic degree of freedom (color singlet) such as  $\rho$  exchange for example.

## 2 A toy model applied to the L=0 SU(3) nonet

In our toy model, decay amplitudes for  $D(D_s)$  to scalar and pseudoscalar mesons are evaluated by making use of the weak effective Hamiltonian at low energy together with QCD factorization. The associated branching ratios are compared to the experimental ones. It leads to make predictions on transition form factors between pseudoscalar ( $B$  and  $D$ ) and scalar ( $f_0(600)$ ,  $K_0^*(800)$ ,  $f_0(980)$  and  $a_0(980)$ ) mesons. We take advantage of these D decays to efficiently constrain, first the scalar meson wave functions and, then the transition form factors derived within a covariant relativistic formalism.

In Covariant Light Front Dynamics[11](CLFD), the state vector, which describes the physical bound state is defined on the light-front plane given by the equation  $\omega r = \sigma$ . Here,  $\omega$  denotes an unspecified light-like four-vector ( $\omega^2 = 0$ ) which determines the position of the light-front plane and  $r$  is a four-vector position of the system. Any four vector describing a phenomenon can be transformed from one system of reference to another one by using a unique standard matrix which depends only on kinematic parameters and on  $\omega$ . The particle is described by a wave function expressed in terms of Fock components of the state vector which respects the properties required under any transformation.

### 2.1 Scalar wave functions

For a scalar particle composed of an antiquark and a quark of same constituent mass,  $m$ , the general structure of the two-body bound state has the form:

$$\phi(\mathbf{k}^2) = \frac{1}{\sqrt{2}} \bar{u}(k_2) A(\mathbf{k}^2) v(k_1) , \quad (1)$$

where  $A(\mathbf{k}^2) = N_S \exp[-4\nu\mathbf{k}^2/m^2]$  is the scalar component of the wave function.  $N_S$  and  $\nu$  are parameters to be determined from experimental  $D$  branching ratios ( $D \rightarrow \text{scalar } \pi$  or  $D \rightarrow \text{scalar } K$ ) and theoretical assumptions.

## 2.2 Transition form factors between pseudoscalar and scalar

In CLFD, the approximate transition amplitude between a pseudoscalar,  $P$ , and a scalar,  $S$ , explicitly depends on the light front orientation:

$$\langle S(P_2) | J^\mu | P(P_1) \rangle^{CLFD} = (P_1 + P_2)^\mu f_+(q^2) + (P_1 - P_2)^\mu f_-(q^2) + B(q^2) \omega^\mu, \quad (2)$$

where  $B(q^2)$  is a non-physical form factor which has to be zero in any exact calculation. Simple algebraic calculations allow us to extract the physical transition form factors  $f_\pm(q^2)$ , by means of the amplitude  $\langle S(P_2) | J^\mu | P(P_1) \rangle^{CLFD}$ :

$$\langle S(P_2) | J^\mu | P(P_1) \rangle^{CLFD} = \int_{(x, \tilde{\theta}, \mathbf{R}_\perp)} D(x, \tilde{\theta}, \mathbf{R}_\perp) \text{Tr} \left[ -\bar{\vartheta}_S(m_1 + \not{k}_1) \gamma^\mu \gamma^5 (m_2 + \not{k}_2) \vartheta_P(m_3 - \not{k}_3) \right] \frac{1}{1 - x'}, \quad (3)$$

which is derived from the usual triangular diagram describing transitions between mesons.  $D(x, \tilde{\theta}, \mathbf{R}_\perp)$  is the invariant phase space element and  $\vartheta_P$  and  $\vartheta_S$  denote respectively the initial pseudoscalar and final scalar wave functions. For more informations on the CLFD approach, we refer the reader to the paper[11].

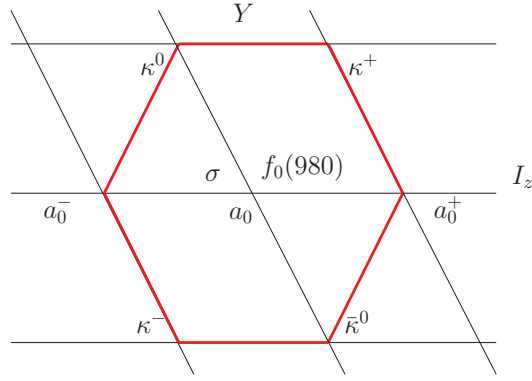
## 3 Conclusion

Using normalization and  $D$  experimental branching ratios one can model the wave function of scalar mesons for which some  $x$  distributions are given in fig. 2a). One can also make predictions on transition form factors between pseudoscalar and scalar mesons as shown (similar results for  $D \rightarrow \text{scalar}$  transitions) in fig. 2b). All the results given here are only qualitative due to some uncertainties among them the experimental  $D$  branching ratios, the 2-quark description assumption and the meson and quark mass effects. It is therefore crucial to improve our understanding of scalar mesons as they play a major role when analyzing for example the  $CP$  violation asymmetry in  $B \rightarrow \pi\pi\pi(K)$ . Better one knows the unitarity triangle, better one can look for new physics effects, however tiny they may be.

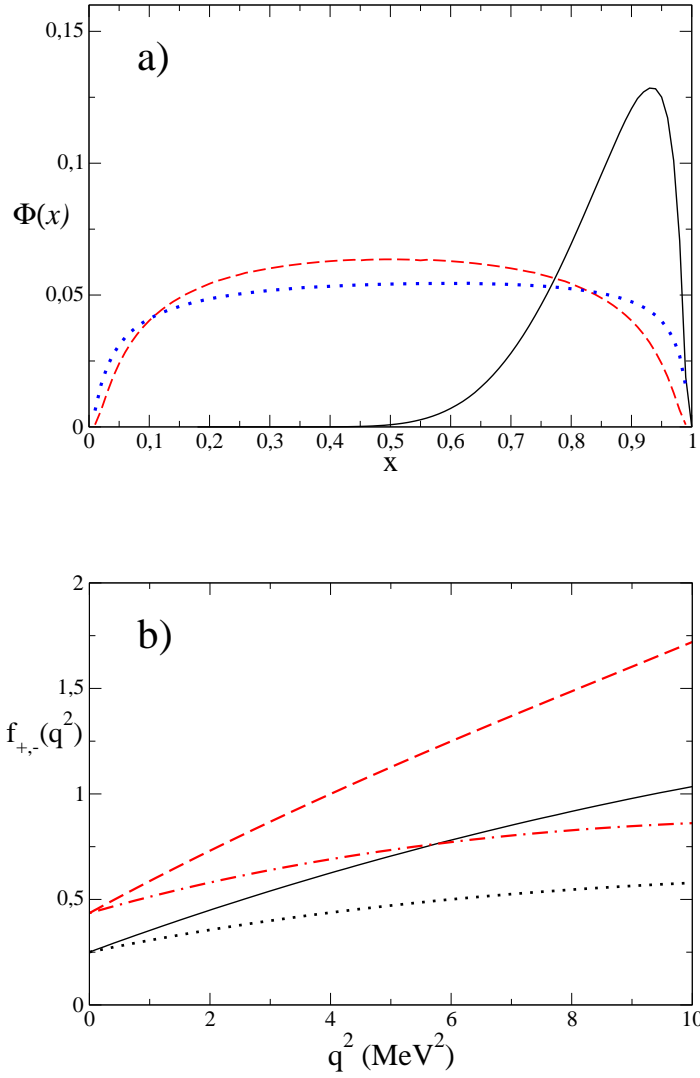
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**Figure 1:** *The  $SU(3)$  nonet*



**Figure 2:** *a)  $x$ -distributions for the  $B$  meson (full line) as well as for  $K^*(800)$  (dashed line) and  $a_0(980)$  (dotted line). b) transition form factors,  $f_+(q^2)$ ,  $f_-(q^2)$ , plotted in case of  $B \rightarrow f_0(600)$  (full and dotted lines) and  $B \rightarrow a_0(980)$  (dashed and dotted-dash lines), respectively.*